Populations of Supersoft X-ray Sources:
Novae, tidal disruption, Type Ia supernovae, accretion-induced collapse, ionization, and intermediate-mass black holes?

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Observations of hundreds of supersoft x-ray sources (SSSs) in external galaxies have shed light on the diversity of the class and on the natures of the sources. SSSs are linked to the physics of Type Ia supernovae and accretion-induced collapse, ultraluminous x-ray sources and black holes, the ionization of the interstellar medium, and tidal disruption by supermassive black holes. The class of SSSs has an extension to higher luminosities: ultraluminous SSSs have luminosities above 10^{39} erg s^{-1}. There is also an extension to higher energies: quasisoft x-ray sources (QSSs) emit photons with energies above 1 keV, but few or none with energies above 2 keV. Finally, a significant fraction of the SSSs found in external galaxies switch states between observations, becoming either quasisoft or hard. For many systems "supersoft" refers to a temporary state; SSSs are sources, possibly including a variety of fundamentally different system types, that pass through such a state. We review those results derived from extragalactic data and related theoretical work that are most surprising and that suggest directions for future research.

1 Introduction

1.1 Nearby SSSs: A small, exclusive group

Supersoft x-ray sources (SSSs) are unusual among x-ray sources because they emit few photons with energies above 1 keV. They are unusual in another way: the definition of the class is very general and can in principle encompass many different types of physical systems.

SSSs were established as a class by *ROSAT* in the early 1990s. The original definition of SSSs is often expressed as follows: luminosities in the range of approximately $10^{36} - 10^{38}$ erg s^{-1} and effective temperatures with kT in the range of tens of eV. This phenomenological definition is based on the detection of a small number of sources. By 1996, seven SSSs had been discovered in the Galaxy, and eleven in the Magellanic Clouds (Greiner 1996).

The empirical definition of SSSs suggests effective radii comparable to the radii of white dwarfs. Indeed, some SSSs are associated with hot white dwarfs in recent novae or symbiotic binaries, or with the central stars of planetary nebulae.

Not all SSSs are associated with systems known to contain white dwarfs. Roughly half of those with optical IDs are binaries with orbital periods ranging from hours to a few days. These close-binary supersoft sources (CBSSs) may be

white dwarfs accreting at high enough rates to allow incoming matter to undergo quasisteady nuclear burning. van den Heuvel et al. (1992) developed a model in which a Roche-lobe filling donor which is more massive than the white dwarf and/or slightly evolved can provide mass at the requisite high rates ($\sim 10^{-7} M_\odot$ yr^{-1}).

The CBSS model was important not only as a possible explanation of SSSs, but also because it provided a channel through which white dwarfs could retain accreted matter, thereby avoiding nova explosions that would deplete the white dwarf. Genuine mass retention by a white dwarf is exciting because it provides a way for some white dwarfs to achieve the Chandrasekhar mass and to undergo accretion-induced collapse (AIC; van den Heuvel et al. 1992) or Type Ia supernova explosions (Rappaport, Di Stefano & Smith 1994).

Although the white dwarf models seemed ideally suited to the first group of SSSs that had been discovered, other explanations were naturally explored as well. Kylafis and Xilouris (1993) considered a neutron star model in which the photospheric radius is comparable to the radius of a white dwarf.

Stellar-mass black holes sometimes exhibit states referred to as "high soft" or "thermal dominant" states (Remillard & McClintock 2006). In these cases, however, the effective values of kT are around 1 keV, making the sources much harder than SSSs. Nevertheless, CAL 87, a Magellanic Cloud source often referred to as one of the "classical

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SSSs", has been considered as a black hole candidate (Cowley et al. 1990).

During the past 17 years, more information has been gathered about the SSSs in the Galaxy and in the Magellanic Clouds. Much of the new data is consistent with white dwarf models. Yet, definite identification of the nature of the accretors has proved difficult.

1.2 External Galaxies: An extended arena

The small population of 16 SSSs found by *ROSAT* in M31 represents a total population that could be as large as $\sim$ 1000 (Di Stefano & Rappaport 1994). The advent of *Chandra* and *XMM-Newton* provided the opportunity to discover more of the M31 SSSs and to identify SSSs in a variety of other external galaxies. Discovering more SSSs allows us to establish the full range of source properties and the distributions of temperatures and luminosities. Clues to the natures of the sources can be gathered by studying their location within galaxies. For example, are SSSs associated primarily with old or young stellar populations? Are the numbers of SSSs in typical galaxies large enough to support the hypothesis that they are the dominant class of Type Ia progenitors?

After a decade of extragalactic x-ray surveys, we can begin to answer some of these questions. Beyond this, we have made discoveries along new lines that reveal SSSs to be an even more interesting class of sources than many of us anticipated. In this short paper we summarize the results that are most surprising and that suggest new lines of investigation.

2 Ten Years of Surprises

2.1 SSSs Near Galactic Nuclei

Only two external galaxies in the Local Group, M31 and M32, are known to have supermassive black holes. Because of the relative proximity of these galaxies, *Chandra* is able to resolve x-ray sources with L_x greater than approximately 10^{36} erg s^{-1} within a few arcseconds of the nucleus. In M32, Ho et al. (2003) find three sources within $30''$ of the galactic center. One of these is the nucleus itself, a $2.5 \pm 0.5 \times 10^6 M_\odot$ black hole. The source closest to the nucleus lies $1.5''$ away, roughly 7 pc, in projection. It is an SSS which can be fit by a 40 eV thermal model or by a power-law model with $\Gamma = 9.2^{+1.7}_{-1.4}$ and $L_X = 2.2 \times 10^{36}$ erg s^{-1}. Because SSSs constitute a relatively small fraction of all x-ray sources, it seems remarkable that the closest x-ray source to the supermassive black hole happens to be an SSS. Interestingly enough, however, the situation in M31 is similar. Within a few arcseconds of the black hole is a soft source, marginally hotter than the "classical" SSSs known in the Magellanic Clouds (Di Stefano rt al. 2004). It is unlikely to be coincidental that very soft sources lie so close to the central black hole in the only two galaxies within which such a phenomenon can be detected. There may be several possible explanations.

One possibility is that the soft sources are the cores of giant stars that have been tidally disrupted by the supermassive black hole (Di Stefano et al. 2001). Tidal disruption is a well-studied phenomenon from the theoretical perspective (Rees 1988; Loeb & Ulmer 1997; Ulmer 1999). The flare which follows such a disruption can be bright ($> 10^{44}$ erg s^{-1}), and can last for days to months. In recent years, flare events that may be associated with tidal disruptions in distant galaxies have been detected (see, e.g., Esquej et al. 2008). When the disrupted star is a giant[1], the remnant is a long-lasting ($> 10^3$ year) hot core that could be detected as an SSS. The computed rate of disruptions (Magorrian & Tremaine 1999) is high enough that large galaxies may each house several stripped cores.

Whatever the natures of the soft sources in the nuclei of M31 and M32, the tidal stripping of cores is a definite prediction, and must produce an excess of soft x-ray sources in the central regions of some galaxies. The sources may be on orbits that bring them far from the nucleus, even while still hot enough to be detected at x-ray wavelengths This means that tidal disruption can have long-lasting consequences that are detectable in nearby galaxies, even though flares are rare and are therefore preferentially observed in very distant galaxies.

This example shows that some SSSs in galaxy centers may have evolutionary paths different from those computed for supersoft sources descended from primordial binaries.

2.2 SSSs in Young Stellar Populations

In the CBSS model derived by van den Heuvel et al. (1992), the requisite high rate of accretion is produced by the thermal time scale adjustment of the donor star to a shrinking Robe lobe. Dynamical stability dictates that the initial donor mass be less than roughly $2.5 M_\odot$ (see, e.g., Langer et al. 2000). In a second class of CBSS models, the white dwarf is fueled by irradiation-driven winds from a donor that is even less massive (van Teeseling & King 1998). Given this mass range, most CBSSs should begin their period of high mass transfer and possible SSS-like activity more than 10^9 years after the binary is formed. The primary must first have a chance to evolve to become a white dwarf. Once it does, there is generally a wait time before the donor can begin to contribute mass. The orbit must shrink (most likely to occur through magnetic braking) and/or the donor must begin to evolve. In either case, the binary has time to move away from the place where it formed. We would therefore not expect SSSs to be primarily associated with regions containing young stars.

It was therefore surprising to find, even in the first *Chandra* observations of the disk of M31 (Di Stefano et al. 2004), that SSSs in the disk are clustered near star-forming regions, possibly indicating that they are young. This result was confirmed and strengthened by observations of other galaxies

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[1] Only giants can be disrupted by black holes with mass larger than about $10^8 M_\odot$, because main sequence stars cross the event horizon before being disrupted.
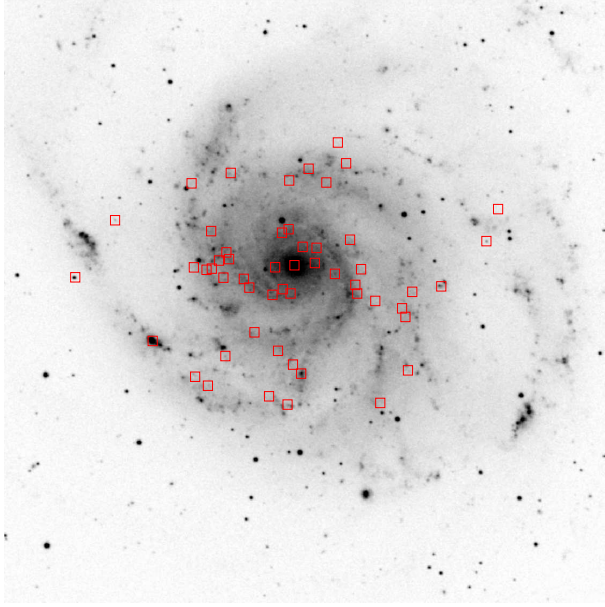
Fig. 1 SSSs in the spiral galaxy M101. SSSs are found in the bulge, but most cluster in or near the spiral arms. Whatever their nature(s), SSSs can ionize the ISM (Rappaport et al. 1994; Chiang & Rappaport 1996). So far, searches for nebulae associated with SSSs have had limited success (Pakull & Motch 1989; Remillard et al. 1995)
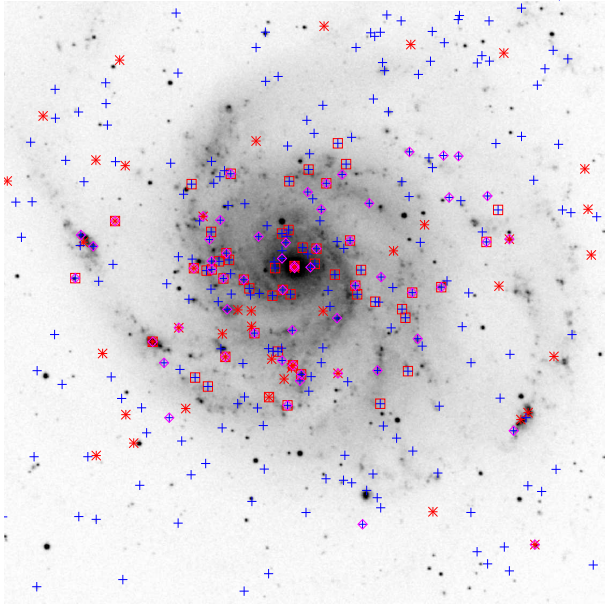

Fig. 2 All x-ray sources in M101. The position of each detected source is marked with a blue cross. As above, red squares mark the positions of SSSs. Red stars correspond to x-ray sources with $L_X > 10^{38}$ erg s^{-1}. Red diamonds are for quasisoft sources (§2.3.2 and Figure 3) **Note that the distribution of x-ray sources is far more extended than the distribution of SSSs. Furthermore, many x-ray sources (and few SSSs) occupy the area between spiral arms.**

(Di Stefano & Kong 2004). Liu (2008) has identified SSSs in 383 galaxies. The location of SSSs in M101 relative to other sources and to the optical features of the galaxy is shown in Figures 1 and 2.

The connection with star-forming regions confirms that many sources are young. The donors are likely to be significantly more massive than white dwarfs. They therefore cannot stably transfer mass to a white dwarf through the L1 point. Instead, they are likely to be contributing mass through a wind. Many SSSs near star-forming regions may be high-mass x-ray binaries (HMXBs) or symbiotic binaries.

2.3 Empirical Extensions of the Class

One of the surprises of population studies is that the class of SSSs has extensions to both higher luminosities ($> 10^{39}$ erg s^{-1}) and higher energies (kT in the range of a $150 - 350$ eV).

2.3.1 Ultraluminous SSSs (ULSs)

Sources with x-ray luminosities above 10^{39} erg s^{-1} are referred to as ultraluminous x-ray sources (ULXs). Because their luminosities are larger than the Eddington luminosity for a ten-solar-mass object, it has been suggested that some may be intermediate-mass black holes (IMBHs). Some SSSs are ultraluminous; such sources are sometimes referred to as ULSs. Several of these sources are well studied. (See, e.g., Fabbiano et al. 2003; Soria & Ghosh 2009; Mukai et al. 2005; Kong et al. 2004; Kong & Di Stefano 2005). It has been suggested that some are white dwarfs in super-Eddington outbursts and/or white dwarfs with beamed emission. Stellar-mass and intermediate-mass black holes have also been considered.

2.3.2 Quasisoft x-ray sources (QSSs)

When we started to look for SSSs in external galaxies, we expected that there would be a gap between their spectra and the spectra of the canonical hard sources normally associated with neutron star and black hole accretors. Instead, we found a continuum of soft source energies.

In fact, many sources provide some photons above 1 keV, while exhibiting no emission above 2 keV. Sources with kT near 100 eV can have such spectral properties, particularly if they are highly absorbed. Such sources are important, even if one is interested only in white dwarfs, because they could be accreting white dwarfs with mass close to the Chandrasekhar mass.

It could therefore have been the case that the harder soft sources were merely highly absorbed hot white dwarfs. To test this hypothesis, we identified all of the sources in several external galaxies, with the goal of finding a significant number of soft sources bright enough for reliable spectral fits. This process identified both absorbed sources with kT in the supersoft range and sources that are intrinsically hotter. (Di Stefano et al. 2006) Indeed, some have fits
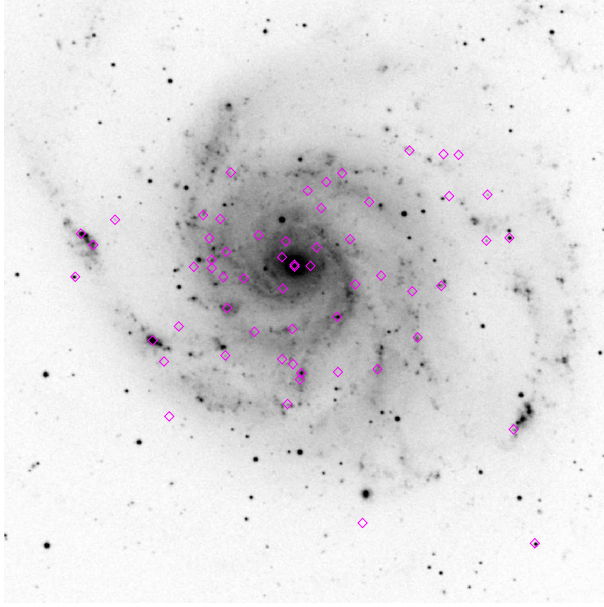
Fig. 3 QSSs in the spiral galaxy M101. Note that QSSs also appear to be concentrated near the spiral arms, although they are somewhat more spread out than SSSs.

with $kT \sim 250 - 350$ eV. These sources are not natural candidates for nuclear-burning white dwarfs (NBWDs). Sources with luminosities above 10^{36} erg s^{-1} which produce few or no photons with energies above 2 keV are called quasisoft x-ray sources (QSSs). QSSs represent a high-energy extension of the class of SSSs. Like SSSs, QSSs have been discovered in every galactic environment. (See Figure 3 and Table 1.)

2.3.3 State-Changing SSSs

The eighteen SSSs comprising the first-discovered set have been observed at occasional intervals over a period of ~ 20 years. Although changes in flux are common, none of the "classical" SSSs have been reported maintain a high luminosity while switching to a harder spectal state. Among the much larger number of sources observed in external galaxies, however, several state changers have been well-documented. One of these is M101-ULS-1. As Figure 4 shows, this source has been detected in supersoft, quasisoft, and hard states. It is very likely a black hole, either of stellar or intermediate mass (Mukai et al. 2005; Kong et al. 2004; Kong & Di Stefano 2005). Two state-changers have been discovered in M31 (Pietsch et al. 2005; Orio 2006; Patel et al. 2009). These are different from M101-ULS-1 in that they are sources of much lower luminosity. They are not likely to be black holes. The light curve of one of the M31 sources is shown in Figure 5.

2.4 Size of the Population

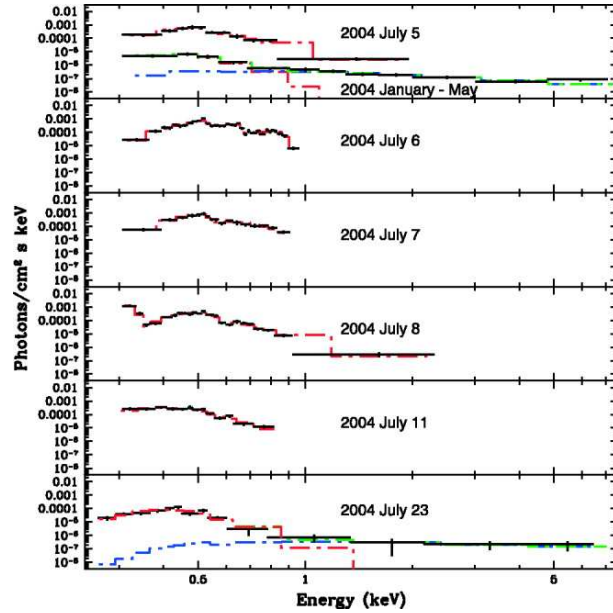SSSs and QSSs have now been discovered in every galactic environment: early type galaxies, in both the bulges and

Fig. 4 Energy distribution of photons received from M101-ULS-1. Note that during some observations all of the photons have energies below ~ 1 keV; the source is supersoft. In others, there is emission above 1 keV, but none above 2 keV; the sources is quasisoft. The source also passes through hard states with lower luminosity than during the soft states. M101-ULS-1 is a considered to be a black hole candidate. Stellar-mass and intermediate-mass models have been considered.

Table 1 Soft Sources in External Galaxies

Galaxy	SSSs	QSSs	Other Sources
M101	42	21	24
M83	28	26	74
M51	15	21	56
M104	5	17	100
NGC4472	5	22	184
NGC4697	4	15	72

spiral arms of late-type galaxies, and in globular clusters. Table 1 shows the results for a set of six galaxies that have each been carefully analyzed. M101, M83, and M51 are spiral galaxies. M104 is a bulge-dominated spiral, while both NGC4472 and NGC4697 are elliptical galaxies. Very soft sources (either SSS or QSS) constitute a larger fraction of all x-ray sources in late-type galaxies. For SSSs there is a dramatic decline in their numbers for early-type galaxies relative to late-type galaxies.

An automated source selection and identification process was employed by Liu (2008) to study x-ray sources in fields containing 383 nearby galaxies. SSSs and QSSs were identified using the same algorithm used for the galaxies in Table 1. Liu found that 2.6% of all sources bright enough for spectral classification are SSS. For every SSS there are four QSSs. The combination of SSSs and QSSs constitute about 13% of all x-ray sources. The high ratio of QSSs to SSSs likely reflects the prevalence of older stellar popula-
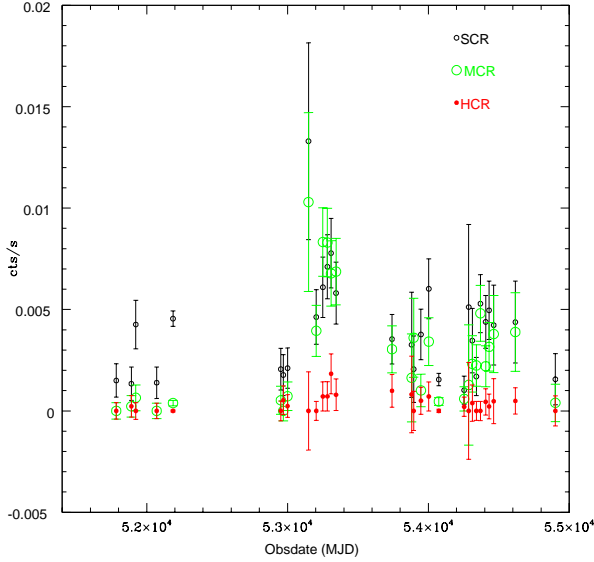
Fig. 5 The light curve of r1-25, an x-ray source in M31. **Black:** count rate in the soft band (0.1-1.1 keV); **Green:** count rate in the medium band (1.1-2 keV); **Red:** count rate in the hard band (2-7 keV). Note that the soft band dominates during the first set of observations, with few or no counts in the medium and hard bands. The source is SSS. In later observations, the count rate is higher in the medium band; during some observations there are significant detections in the hard band. This source passes through SSS, QSS, and hard states. The estimated luminosity in all cases is less than 10^{38} erg s^{-1}.

tions among the galaxies in Liu's survey. In addition, Liu estimates that $\sim 22\%$ of the SSSs are state-changers.

Among the SSSs alone, Liu identifies 5 sources with $L_X > 5 \times 10^{39}$ erg s^{-1}, and 22 sources with $L_X > 1 \times 10^{39}$ erg s^{-1}. In estimating the luminosities, Liu has used a power-law model, which may underestimate the luminosity of the SSSs.

2.5 SSSs as Progenitors of Type Ia Supernovae

In order for an accreting white dwarf to achieve the Chandrasekhar mass and explode as a Type Ia supernova, it must generally gain at least $0.2\,M_\odot$. Retention of matter by WDs appears to require nuclear-burning. The burning of matter releases a great deal of energy, $> 10^{38}$ erg s^{-1} for white dwarf masses near M_C. In the simplest model, these sources should radiate as SSSs, with $kT > 80$ eV.

The progenitors of Type Ia supernovae should be the hottest and brightest SSSs. Di Stefano & Rappaport (1994) showed that those SSSs which are Type Ia progenitors could be detected in nearby galaxies with high efficiency. Because it takes time ($> 2 \times 10^5$ yr) to accrete $> 0.2\,M_\odot$ at rates of $\sim 10^{-6} M_\odot$ yr^{-1}, the numbers of actively accreting, hot,

bright progenitors in galaxies such as our own and M31 must be large.

$$N = 750 \left(\frac{\Delta M}{0.2\,M_\odot}\right)\left(\frac{8 \times 10^{-7}\frac{M_\odot}{yr}}{\beta\,\dot{M}_{in}}\right)\left(\frac{L_B}{10^{10}L_\odot}\right). \quad (1)$$

For most spiral galaxies (and even for ellipticals, with a lower rate of SNe Ia), N cannot be much smaller than several hundred, and is likely to be larger.

Comparing the number of hot, bright NBWDs needed to account for the expected Type Ia supernovae to the numbers of SSSs and QSSs actually detected in each galaxy, we find a discrepancy larger than a factor of ten. In fact, the true discrepancy is almost certainly larger. This is because not all SSSs, and possibly only a small fraction of QSSs, are NBWDs. Furthermore, of those soft sources that are NBWDs, many are too dim and cool for the white dwarf to have a mass near M_C.

Thus, x-ray observations of external galaxies falsify the hypothesis that the majority of Type Ia supernovae are generated by NBWDs that are detectable as SSSs during the epoch in which the white dwarf's mass is increasing. There are two possibilities: either the majority of Type Ia progenitors are not NBWDs approaching the Chanadrasekhar limit, or they are, but we cannot detect them as SSSs.

In fact, it may be the case that those accreting white dwarfs on the way to becoming Type Ia supernovae tend to eject more winds, which can then block the soft radiation and obscure the source. In addition, a low duty cycle of activity, expected for recurrent novae, could also make the sources less likely to be detected in a supersoft phase.

2.6 SSSs and Accretion-Induced Collapse

The most serious bottleneck found in binary evolution calculations of accreting white dwarfs that might be Type Ia progenitors is the difficulty in channeling enough mass to the accretor to allow it to achieve the Chandrasekhar mass. This problem is less severe for those white dwarfs that start with masses within a few tenths of M_C. These tend to be O-Ne white dwarfs which experience AIC when reaching the Chandrasekhar mass, instead of Type Ia explosions.

Because the white-dwarf progenitors of AIC must be massive, the binaries in which they form must be wide. Furthermore, the companion which donates mass to the white dwarf is likely to be massive. AICs are therefore likely to take place near star-forming regions. Before the collapse, the white dwarf is likely to be accreting winds ejected by the donor star, with matter infalling at rates of roughly $10^{-6}M_\odot$ yr^{-1}. The white dwarf should appear as an SSS, at least episodically. After the collapse, the winds will continue. The newborn accreting neutron star will be highly luminous and may appear as a ULX. This model (Di Stefano, Pfahl, & Harris 2009) links the SSSs found near star forming regions with a subset of ULXs. ULXs are also preferentially found near star-forming regions.

2.7 Extensions of the Models

At the time SSSs were discovered, NBWDs provided the most natural explanation for their observed ranges of luminosities and temperatures. Indeed, the significant association between novae and SSSs verifies that many transient SSSs are indeed hot white dwarfs (Pietsch et al. 2005), while observations of nearby CBSSs provide evidence that NBWD models are likely to apply.

In the time since the early 1990s, however, two developments argue for extensions of the physical models. The first development is the extension of the ranges of source temperatures and luminosities described in §2.4. The discovery of QSSs and ULSs provide examples of systems that are too hot and/or too luminous to be white dwarfs.

The second development is the consideration of higher-mass black holes. First, black holes with masses between $15\,M_\odot$ and $33\,M_\odot$ (Orosz et al. 2007; Prestwich et al. 2007) have been discovered. Second, IMBH models have been developed as explanations of ULXs. For black hole accretors with masses larger than a few solar masses, an optically thick inner disk can emit as a QSS or SSS. (See Figure 6.) If the system is in a thermal dominant state, the state in which it is possible determine the black hole mass, it may appear as a QSS or, for more massive black holes, as an SSS. (See Di Stefano et al. 2003a, 2003b, 2004a, 2004b; Di Stefano & Kong 2003a, 2003b, 2004a, 2004b)

While back hole models are natural for some QSSs and SSSs, neutron star models should also be reconsidered. During the early 1990s, when the only known neutron star accretors were hard x-ray sources, it seemed to require fine tuning to achieve a white-dwarf-like photospheric radius. The discovery of QSSs allows a wider range of photospheric radii, perhaps removing the need for fine tuning. In addition, white dwarf models in which a cooling white dwarf produces soft radiation, but harder emission is produced through accretion, can also be used to model state-changing soft sources (Patel et al. 2009).

Conclusions: SSSs are found in all galactic environments. Many are young stellar systems. Several evolutionary paths can produce soft sources, while not all NBWDs, even those of high mass, are detectable as SSSs. The sum of these discoveries suggest that soft x-ray sources provide a rich area for research on many astrophysical topics of great interest.

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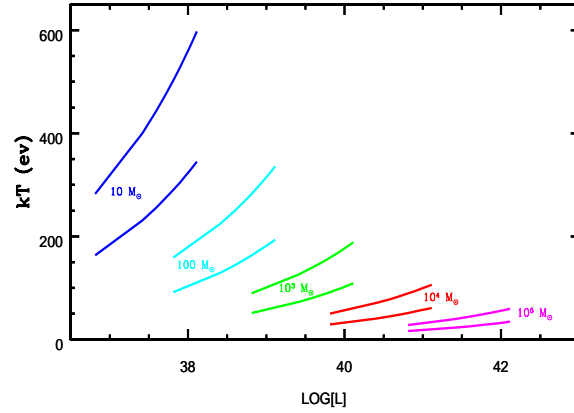
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Fig. 6 kT versus $Log[L]$ for the inner portion of the accretion disk around black holes. Each pair of two curves of a single color corresponds to a fixed black hole mass which labels the regions between the curves. The upper curve of each color corresponds to a disk with inner radius $6M_{BH}G/c^2$, while the lower curve corresponds to an inner disk with 3 times the radius. The point at the bottom (top) of each curve corresponds to the luminosity of the inner disk being $1\%L_{Eddington}$ ($10\%L_{Eddington}$).

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